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CALCULATION OF DOSE CONSEQUENCES OF A HYPOTHETICAL LARGE ACCIDENT AT A NUCLEAR POWER REACTOR

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Abstract. The fission-product release to the atmosphere from a nuclear reactor during a hypothetical large accident is discussed, and the consequences in terms of doses to the population are calculated. The reactor is a light-water reactor located at a site representing an idealized, simplified Danish location.

Three release categories are discussed: The first is the release in an accident with a core meltdown and a major rupture of the containment. This release is represented by the BWR-2 release of WASH 1400. The second is the release where the containment integrity is maintained, but there is a failure to isolate the containment. This release is represented by the PWR-4 release. The third is obtained as a best estimate from empirical data, and it is called the BEED release. The release of the BEED case is deduced from empirical evidence - especially the SL-1 accident - in a separate study which is described in the appendix. The release fractions for the most significant elements such as iodine and cesium decrease by a decade from BWR-2 to PWR-4, and from PWR-4 to BEED, while the release fractions of the noble gases are assumed to be at an almost constant high level.

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The dose consequence in terms of a long-term committed effective dose equivalent is found to be practically directly proportional to the release fractions, i.e. decreasing by a decade from BWR-2 to PWR-4, and from PWR-4 to BEED. For the acute bone marrow dose the contribution from the noble gases is significant in all three cases, and as the noble gas release is almost constant the decrease from one case to the next is of the order of only half a decade. For the BEED case the noble gases, which give an external gamma dose from the plume, are the most significant radioactive fission products, both for long-term and acute doses. For the BWR-2 and PWR-4 cases the I-131 in the plume is predominant in the acute dose, while Cs-137 deposited on the ground is the main contributor to the long-term dose.

INIS descriptors: BWR TYPE REACTORS; CESIUM 137; FISSION PRODUCT RELEASE; HUMAN POPULATIONS; IODINE 131; MELTDOWN; PWR TYPE REACTORS; RADIATION DOSES; RADIATION HAZARDS; RARE GASES; REACTOR ACCIDENTS.

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1. INTRODUCTION

In this study the fission-product release to the atmosphere from a nuclear reactor during a hypothetical, large accident is discussed, and the consequences in terms of doses to the population are calculated. The reactor is a light-water reactor located at a site representing an idealised, simplified Danish location.

The main parameter in this study is the fission-product release and three cases are studied:

- A fission-product release as in a BWR-2 type accident (WASH-1400 nomenclature)
- A release as for a PWR-4 type accident,
- A release, obtained as a best estimate from the empirical data available, for a reactor system with a reducing atmosphere. This case is called BEED below.

The many parameters in this study that describe the physical conditions, e.g. the weather situation and the deposition velocities, are in general chosen so that representative conditions are obtained.

2. ACCIDENT TYPES AND FISSION-PRODUCT RELEASES

2.0. The Large Accident

The large accident considered here for a nuclear power reactor is a hypothetical accident, where it is assumed that a full core meltdown takes place for a power reactor. This type of accident has never taken place anywhere, and all information on the consequences comes from theoretical analyses of hypothetical acci-

dent sequences. WASH-1400 (The Rasmussen Report) is the main source for analysing the accident sequences, the consequences, and the probabilities of the accidents, thus yielding the total risk to the population. In WASH-1400 the probability of a core meltdown is calculated to be 5×10^{-5} per reactor-year.

An operating nuclear power reactor core contains a huge amount of radioactivity (see Table 2). The releases from a melted core to the environment depend on the behaviour of the molten core material in the pressure vessel and containment, and the released fission-product paths through the containment and surrounding buildings to the open air. The behaviours of a melted core and of fission products on the scale of a power reactor are to be extrapolated either from experiments on a very small scale compared with the reactor, or from accidents experienced in actual reactors, where releases of the magnitude envisaged in the theoretical studies have never been approached.

In the following, three cases with different levels of releases are discussed. The discussion relies to a large extent on the analysis of WASH-1400, and the object of interest is the fraction of the fission products in the core that is released to the atmosphere. The study here does not contain a full accident sequence and risk analysis, and the probabilities estimated below are inferred from the results of WASH-1400.

2.1. BWR-2

The first case is defined by the release category of BWR-2 in WASH-1400. This is one of the largest releases, where a significant fraction of fission products is released to the atmosphere (see Table 1). (The release fractions of the "big" cases of WASH-1400: PWR-1, PWR-2, BWR-1 and BWR-2, are of the same order of magnitude). The category was chosen here because it was used in earlier Danish studies for the Barsebäck reactor (Hedemann Jensen et al, 1977).

The BWR-2 category involves a loss of all decay heat removal leading to a rupture of the containment due to overpressure.

The core melts down after the containment rupture and as a result the released fission product fraction is high. The probbability of a BWR-2-type accident is 6×10^{-6} per reactor year according to WASH-1400.

2.2. PWR-4

The consequences of an accident depend strongly on whether the the containment fails or not, and if it does fail, on the failure mode and the time lag.

Recent research, at the moment primarily directed towards PWRs, has led to an estimated probability of a containment failure following a core meltdown that is smaller than that found by the WASH-1400 programme.

Experimental work at Sandia Laboratory in USA indicates that the probability of a steam explosion in the reactor vessel, which may cause containment failure, is two orders of magnitude lower than assumed in WASH-1400 (Berman et al, 1980). The probability of the most serious PWR release category in Wash-1400, category 1, is thus reduced by two orders of magnitude.

In Germany, at the Kernforschungszentrum Karlsruhe, theoretical and experimental work have shown that for a German PWR the time from a core melt until the overpressure failure of the containment due to steam and gas generation and hydrogen burning, is 2-3 days (Rininsland et al, 1980). The melt-through of the concrete base mat in the containment is unlikely, and if it does occur, will take several months. It has also been shown that the concentration of radioactive materials in the containment atmosphere in 2-3 days will have decreased by 3-5 orders of magnitude. Thus the amount of radionuclides available for release to the environment at the time of containment failure is very small. It turns out that the release during the accident

will be determined by the leak rate from the containment. For an isolated containment the design leak rate may be 0.25% of total volume per day. If the leak rate equals the design leak rate the amount of released radionuclides in accident sequences, which in WASH-1400 would give category 2 and 3 releases, will be 10^{-2}-10^{-3} times the WASH-1400 results. This is caused by the longer time interval between core melt and the containment failure in the new calculations, and the more refined models used for calculating the aerosol behaviour in the containment.

Based on these results, it appears that the most probable serious consequences of core meltdown in a PWR will not come from the accident sequences described by PWR-1, -2 and -3, but from an accident sequence that includes a failure to isolate the containment.

In WASH-1400 the PWR release category with a melted core and a non-isolating containment (and the containment radioactivity removal system failing as well) is PWR-4. Without going into a detailed study here of accident sequences leading to this situation, the PWR-4 release is taken as representative of the case.

The probability of this release under these new assumptions, where the probabilities of the WASH-1400 PWR-1, -2 and -3 releases are considered to be extremely small, is assumed here to equal the sum of the probabilities of PWR-1, -2, -3 and -4, i.e. $\sim 1.4 \times 10^{-5}$ per reactor year.

The PWR-4 release fractions are shown in Table 1. The PWR-4 release is roughly a factor of ten lower than for BWR-2, except for the noble gases, Xe-Kr. The PWR-4 release starts early, after 2 hours, due to the failure to isolate.

2.3. BEED

Recently scientists in the USA have re-evaluated the information available from reactor accidents, like that at Three Mile Island, and they have reported their findings: Only

a small fraction of the fission products in the reactor core is released to the atmosphere (Stratton et al, 1980, Levenson and Rahn, 1980). The most important radionuclide, I-131, is not released; instead cesium iodide is, and this combines with the water in the system of a LWR, so that only a small fraction of the I-131 is available for release to the atmosphere.

A study of data from actual reactor accidents such as SL-1, Windscale, and TMI, was made a part of this work, and the discussion of the conclusions to be drawn from the empirical data is given in the appendix. The data in the literature are often incomplete with respect to the measured results wanted here, but the conclusion of the study is that the empirical evidence shows that for a reactor system with a reducing water and steam environment, as in an LWR system, the release of fission products will be less than 1% of the core content (except for the noble gasses). This reduction is due to physical and chemical processes in the fuel, water, and buildings, and it is assumed here, as was argued above in the PWR-4 case, that the probability of an instantaneous removal of all containment isolation is exceedingly low, so that some amount of containment isolation and reducing atmosphere is maintained.

The fission-product release obtained as a best estimate from empirical data, when the reactor system has a reducing atmosphere, is in the table and in the figures called BEED. The release fractions are given in the appendix and are shown in Table 1.

The probability of an accident leading to a BEED category release is estimated here for simplicity to be equal to the probability above in 2.2 for the redefined PWR-4, i.e. equal to 1.4×10^{-5} per reactor year.

The BEED release fractions are roughly a factor of 100 lower than those of BWR-2, and a factor 10 lower than those of PWR-4 except for the noble gasses (see Table 1). The BEED release is assumed to start early, after 2 hours, like that for the PWR-4.

3. REACTOR SURROUNDINGS. CALCULATION MODELS AND PARAMETERS

3.1. Reactor surroundings

The nuclear power reactor is placed at an east coastal point, with the land covering 180° towards the west.

The population density is

0–5 km	50 persons/km^2
> 5 km	100 " "

The average population density of Denmark is 120 persons/km^2, and the site defined above is a simplified and idealised version of a Danish site. It was considered in the study to place a major town of 2-300,000 inhabitants in the picture, but this was omitted here, mainly because of the amount of extra work in comparing the many curves and results. The population as a function of distance from the reactor site is given in Table 3.

3.2. The reactor

The reactor is a light-water reactor of 2000 MW_{th}, corresponding to ~ 600 MW_e. This size was chosen because it was used in earlier Danish studies.

3.3. Fission-product releases

The fission products produced in the reactor core are given in Table 2. The release fractions to the atmosphere are discussed above in Section 2. The fractions and characteristic time of release are given in Table 1.

3.4. Dosimetric model

The Risø dose-consequence model, PLUCOM2, has been used for the calculation of individual and collective doses.

The dispersion model used in PLUCOM2 is the so-called Gaussian model. In this model it is assumed that the material released to the atmosphere will be carried with the wind and spread like a smoke plume. The most important atmospheric parameters are the wind direction, wind speed, and vertical temperature gradient because these determine the transport direction, dilution at the moment of release, and turbulent mixing.

The Gaussian model has been verified out to distances of 20 to 30 km where it is able to predict doses and concentrations within a factor of 2 - 3. At larger distances, doses and concentrations normally are overestimated. This overestimate can be as large as a factor of 10 at 50 km.

Plume rise due to the heat content of the released material is taken into consideration. The rise of the plume is calculated according to a formula given by Briggs.

In the model both dry deposition and wash-out of the material in the plume is taken into consideration. Dry deposition is calculated according to the source depletion model.

The total dose to an individual is calculated as the sum of three dose components:

Inhalation dose
External gamma dose from the plume
External gamma dose from material deposited on the ground.

The collective dose within a given area is calculated as the sum of the doses to the individuals within the area. Evacuation has not been taken into account.

A detailed description of PLUCON2 is given in Thykier-Nielsen (1980).

3.5. Meteorological parameters

The meteorological conditions applied in all calculations of individual and collective doses are realistic conditions for a Danish reactor site. The meteorological conditions chosen are:

Neutral stability (Pasquill category D)
Wind speed 6 m/s
Mixing height 1000 m
No rain
Wind from east (wind blowing towards west (270 deg.))

Wind direction, atmospheric stability, and wind speed are correlated. Based on Risø's meteorological statistics from the period 1958 to 1967 (see Jensen 1973) the probabilities (in per cent) are as follows:

	Wind directions		
	All	East (0^o-180^o)	Strict east (75^o-105^o)
Probabilities of wind from east and strict east, respectively	100	42	7.4
Probability of Pasquill D (given the considered wind directions)	60	58	55
Probability of wind speeds 6 m/s to 10 m/s (given the considered stability and wind directions)	40	38	33
The joint probabilities of the wind directions considered, Pasquill D and wind speeds from 6 m/s to 10 m/s	24	9.3	1.4

Probabilities (per cent) of meteorological conditions.
The probability of no rain when the stability is neutral is 80% to 90%.

3.6. Parameters for dose calculations

The dose calculations are based on the meteorological situation specified in 3.5 and the following assumptions:

3.6.1. Deposition

No wet deposition
Dry deposition velocities:
Iodine: 0.01 m/s
Noble gases: No deposition
Other isotopes: 0.002 m/s

The choice of dry deposition velocities is based on Roed (1981) and Nielsen (1980).

3.6.2. Dose calculations

Inhalation doses

During the overhead passage of the plume, a person standing on the ground will inhale an amount of radioactive material proportional to the passage time and the concentration at the location in question.

The total inhalation dose integrated over a given period of time after the activity was inhaled is calculated by multiplying the amount of each radionuclide inhaled with a dose-conversion factor for this particular radionuclide, and then adding these products.

The dose-conversion factor for a given radionuclide is equal to the dose per unit intake (in, e.g. Bq) integrated over a given period of time after the intake.

The inhalation doses are reduced by the filtration effect of houses. Here a reduction factor of 0.2 for filtration is used.

This has been derived from recent Danish investigations (see Gjørup and Roed, 1980).

External dose from the plume

The decay of radionuclides is associated with the emission of radiation in the form of γ-photons.

The external γ-dose from the cloud is calculated by assuming that the cloud is composed of an infinite number of point sources and deriving the total dose by integration. Attenuation and multiple scattering of the γ-rays in the air are included in the calculation of the dose from each point source. The γ-dose in the air is equal to the γ-flux density multiplied by the mass energy absorption coefficient for each of eight γ-energy groups.

Inside buildings, the external gamma dose from the plume will be reduced considerably due to the shielding effect of the structure. In this report it is assumed that people remain indoors in brick buildings during the entire passage of the plume.

A shielding factor of 0.6 has therefore been applied. This factor is given in WASH-1400 as representative of single-family houses and multi-storey brick buildings.

External dose from deposited activity

The external γ-dose from deposited activity is calculated by the same principles as the external dose from the plume; the ground is divided into a number of point sources and their dose contributions are integrated. By convention the dose in air is calculated at a point 1 m above the ground.

In this study it is assumed that people stay indoors for the first 24 hours after the release has started. When the 24 hours have passed, it is assumed that they are outdoors 11% of the time. A shielding factor of 0.0769 is assumed in accordance with Gjørup (1981).

In this study both acute and long-term doses have been studied:

Acute doses to the bone marrow

Acute doses to the bone marrow have been calculated as the sum of:

1. The external gamma dose from the cloud.

2. The external gamma dose from activity deposited on the ground integrated over 24 hours.

3. The internal dose received during the first 30 days after inhalation of activity from the cloud. (The main part of the dose to the bone marrow is received within 30 days).

Long-term, committed effective dose equivalent to the whole body

The long-term consequences of irradiation to the whole body is assessed from the committed effective dose equivalent. This is calculated here as the sum of:

1. The external gamma dose from the cloud

2. The external gamma dose from deposited radionuclides integrated over
   a. 24 hours,
   b. 30 days, and
   c. 30 years.

3. The committed effective dose equivalent from inhalation of radionuclides during cloud passage. The calculation of this dose equivalent is based on an integration of the internal effects over 50 years, and it follows ICRP recommendations (see Table 4).

The (total) committed effective dose equivalent is labelled according to the integration time (24 h, 30 d, 30 y) for the external gamma dose from deposited radionuclides or, in other words, the period of staying.

4. CALCULATION RESULTS

The individual and collective doses calculated for the release categories BWR-2, PWR-4, and BEED are shown in Figs. 4.1-4.8.

In Figs. 4.1-4.4 the individual doses from the 3 release categories are compared.

4.1.

The 30-year committed effective dose equivalent shows the largest differences between doses from different releases. At distances of 5 km or more the ratio of the doses from BWR-2 and PWR-4 is about 10. The doses from BEED are a factor of 10 lower than those from PWR-4.

At 20 km the doses are:

BWR-2: 89 rem
PWR-4: 8.8 -
BEED : 0.95 -

Unlike the PWR-4 and BEED curves the BWR-2 curves have a pronounced maximum, due to the relatively large heat content and corresponding large effective dispersion height (65 m). In the PWR-4 and BEED cases the effective dispersion height is only 8 m.

4.2.

The differences are smaller for acute bone marrow doses (Fig. 4.2). At distances of 5 km and more the doses from PWR-4 are a factor of 5 less than those from BWR-2. The BEED doses are about a factor of 10 less than those from BWR-2.

The smaller differences between doses compared with Fig. 4.1 are caused by the dose from noble gases constituting a larger part of the acute bone marrow dose than it does of the 30-year committed effective dose equivalent. In the BWR-2-case for example, the dose contribution from noble gases at 5 km constitutes 2.5% of the bone marrow dose while only 0.14% of the 30-year committed effective dose equivalent.

4.3.

The 24-hour (Fig. 4.3) and 30-day (Fig. 4.4) committed effective dose equivalent shows the same pattern as the previous figures as to the relative size of doses from the three releases.

4.4.

When considering long-term consequences of land contamination the question of relocation is important. In Gjørup (1981) several criteria for relocation have been discussed. These criteria might be of the form: If the dose to individuals could be reduced by X rem by moving them 24 hours after the release and letting them return to their home 30 days after the release then they must be relocated. Based on dose reduction criteria of X = 10 rem and data from Figs. 4.3 and 4.4, the maximum distances from the release point where relocation should take place is calculated as

BWR-2	release:	15	km	maximum	relocation	distance	
PWR-4	- :	3.5	-	-	-	-	
BEED	- :	0.9	-	-	-	-	

The relocation distance for the BEED release is a factor of 4 lower than the distances for the PWR-4 release and a factor of 16 lower than those for the BWR-2 release.

4.5.

The collective 30-year committed effective dose equivalent integrated from 0.5 km to 50 km is shown in Figs. 4.5 and 4.9. It is seen from Fig. 4.5 that there is an order of magnitude between the collective doses from the three releases.

The collective doses are:

BWR-2: 1.9×10^6 manrem

PWR-4: 0.21×10^6 manrem

BEED : 0.022×10^6 manrem

The significance of the dose contributions from different isotope groups is also evident from Fig. 4.5 and is further illustrated in the following table:

Isotope group	Release category BWR-2	PWR-4	BEED
Iodine	22	28	30
Noble gases	2	7	41
Others	76	65	29

Relative distribution of collective 30-year committed dose equivalent (per cent).

A comparison of the doses from the BEED-release with those from BWR-2 and PWR-4 shows a significant increase in the relative contributions from noble gases. Note that the decreased release of iodine and other isotopes mainly gives a decrease in the relative dose contribution from the group: "other isotopes".

4.6.

The significance of the doses from different isotope groups is further illustrated in Fig. 4.6, which indicates the total acute bone marrow dose. Doses from the iodine group are dominant in the BWR-2 and the PWR-4 cases even if its significance decreases

with distance due to the large deposition velocity compared with other isotopes. The dose from noble gases is of little significance in the BWR-2 case, while it is dominant in the BEED case.

4.7.

The 24-hour doses to individuals are shown in Fig. 4.7. The most important component of the bone marrow dose is the external gamma dose from the plume. However, it is only in the BEED case that it is the only dose component of importance. This is due to the relatively low release fractions for iodine and other isotopes, which leaves the noble gases in a dominant position concerning doses. The noble gases contribute to the external gamma dose from the plume only and thus this dose component must be dominant in the BEED case.

4.8.

The 30-year whole body doses (Fig. 4.8) have been divided in dose components. In the BWR-2 and PWR-4 cases the doses are governed principally by the external gamma dose from deposited material and to a certain extent by the inhalation dose. In the BEED-release the amounts of iodine and other non-volatile isotopes have been reduced and the external gamma dose from the plume becomes the dominant dose component (about 50% of the total dose at distances of 10 km and more).

4.9.

The collective 30-year whole body dose accumulated from 0.5 km as a function of distance from the release point is shown in Fig. 4.9. The curves have a bend at 5 km due to the change in population density from 50 to 100 persons/km^2. At 50 km the collective doses from the BEED release is one order of magnitude lower than those from PWR-4 and two orders of magnitude lower than the collective doses from BWR-2.

5. CONCLUSION

Recent work (on PWRs) shows that the probability is extremely small of the large accident with a core meltdown, where there is an early, major rupture of the containment, resulting in release of a large fraction of the fission products to the atmosphere. The work on containment integrity is expected to lead to an acceptance of the accident without an early large rupture of the containment as the most realistic description of the hypothetical large accident. The release fractions for the essential radionuclides are in this case one order of magnitude lower than those used for the hypothetical large accident with rupture of containment.

Studies of actual accidents show that the fission products from the reactor core are captured to a large extent through physical and chemical processes in a system with a reducing water-steam atmosphere, and only a small fraction of the fission products is actually released to the open air. When a solid foundation of knowlegde of the processes and scales involved is created through experiments, a realistic assessment can be made of the physical and chemical reduction of the fission product release to the atmosphere. It is expected on the basis of the empirical evidence seen so far that this will lead to releases which are at least an order of magnitude lower than those mentioned above.

The doses to the population are obtained as a complex sum of a series of contributions. It is found that the (long-term) committed effective dose equivalent, individually as well as collectively, is practically directly proportional to the fraction of the fission products released. (This was to be expected as the term "fraction of fission products" is related to the radionuclides predominant in the doses). However, this proportionality is not maintained for the acute bone marrow dose. The reason is that the dose from noble gases constitutes a significant

part of the bone marrow dose, and the release of the noble gases is assumed to be almost the same for all three cases.

The reduced release of iodine and non-volatile radionuclides in the best estimate (BEED) case make the noble gases, which give an external gamma dose from the plume, the most significant contributors, both for the long-term and acute doses. In comparison the acute dose for the BWR-2 and PWR-4 cases is primarily due to I-131 in the plume, and the long-term dose is mainly that of the gamma dose from deposited activity.

The fraction of the fission products released is the most essential parameter in the calculation of dose consequences of a hypothetical large accident at a nuclear power reactor. Future work should be devoted towards creating a solid foundation of knowledge concerning the processes and scales involved in the reactor and its containment during an accident.

6. ACKNOWLEDGEMENT

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Table 1. Fission-product releases

	F.P. release case			
	BWR-2	PWR-4	BEED	
Release time hours after shut-down	30	2	2	hours
Release period	3	3	3	hours
Initial release height	0	0	0	m
Release fractions %				
Xe-kr	100	60	60	%
I-Br	90	9	1	%
Cs-Rb	50	4	0.1	%
Te-Sb	30	3	0.5	%
Ba-Sr	10	0.5	0.02	%
Ru	3	0.3	0.02	%
La	0.4	0.04	0.02	%

Table 2. Fission product content in the reactor core

Isotope	Amount (PBq)	Isotope	Amount (PBq)
Kr 83 m	248	I 131	1910
Kr 85 m	570	I 132	2800
Kr 85	14.6	I 133	3310
Kr 87	1060	I 134	4430
Kr 88	1470	I 135	3810
Rb 86	1.45	Xe 131 m	26.9
Rb 88	1500	Xe 133 m	101
Rb 89	1970	Xe 133	3310
Sr 89	2000	Xe 135 m	738
Sr 90	109	Xe 135	1050
Sr 91	2540	Cs 134	111
Y 90	112	Cs 136	64.5
Y 91	2580	Cs 137	142
Zr 95	3400	Cs 138	3650
Zr 97	3380	Ba 140	3550
Nb 95	3400	La 140	3610
Nb 97	3400	Ce 141	3310
Mo 99	3650	Ce 143	3140
Tc 99 m	3220	Ce 144	2260
Ru 103	2970	Pr 143	3100
Ru 105	1900	Pr 144	2280
Ru 106	732	Nd 147	1310
Rh 105	1800	Pm 147	312
Rh 106	802	Pm 149	1020
Sb 127	107	Np 239	40840
Sb 129	587	Pu 238	1.39
Te 127 m	17	Pu 239	0.639
Te 127	105	Pu 240	0.697
Te 129 m	107	Pu 241	191
Te 129	565	Am 241	0.122
Te 131 m	264	Cm 242	33.8
Te 131	1700	Cm 244	0.639
Te 132	2750		

1 PBq = 10^{15} Bq

Table 3. Population distribution about fictive reactor site. The data are for a 180° sector to the west of the reactor

Distance from the reactor site km	Population	Accumulated population from 0.5 km
0.5-1	59	59
1-2	237	296
2-5	1662	1948
5-10	11237	13185
10-20	47132	60317
20-50	330013	390330

Table 4. Definition of committed effective dose

The committed effective dose equivalent is defined as:

$$H_{50B} = \sum_{T} W_T \times H_{50T}$$

where

H_{50B} = Committed effective dose equivalent

H_{50T} = 50 years committed dose equivalent for target tissue (organ T)

W_T = Weighting factor for target organ T. (The summation involves all body organs).

Data for H_{50B}, H_{50T}, and W_T have been taken from ICRP 30 (ref. ICRP79).

Committed effective dose equivalent. 30 years.

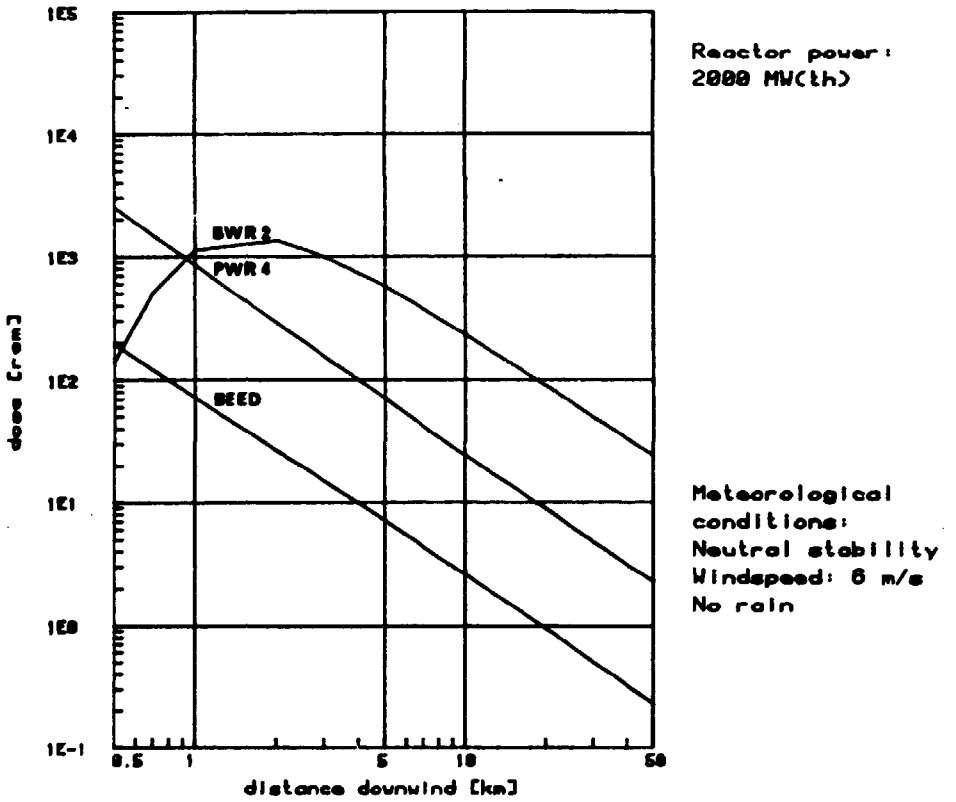

Fig. 4.1

4.1

Total committed effective dose equivalent to individuals from the BWR-2, PWR-4, and BEED releases.

Doses from deposited activity are integrated over 30 years.

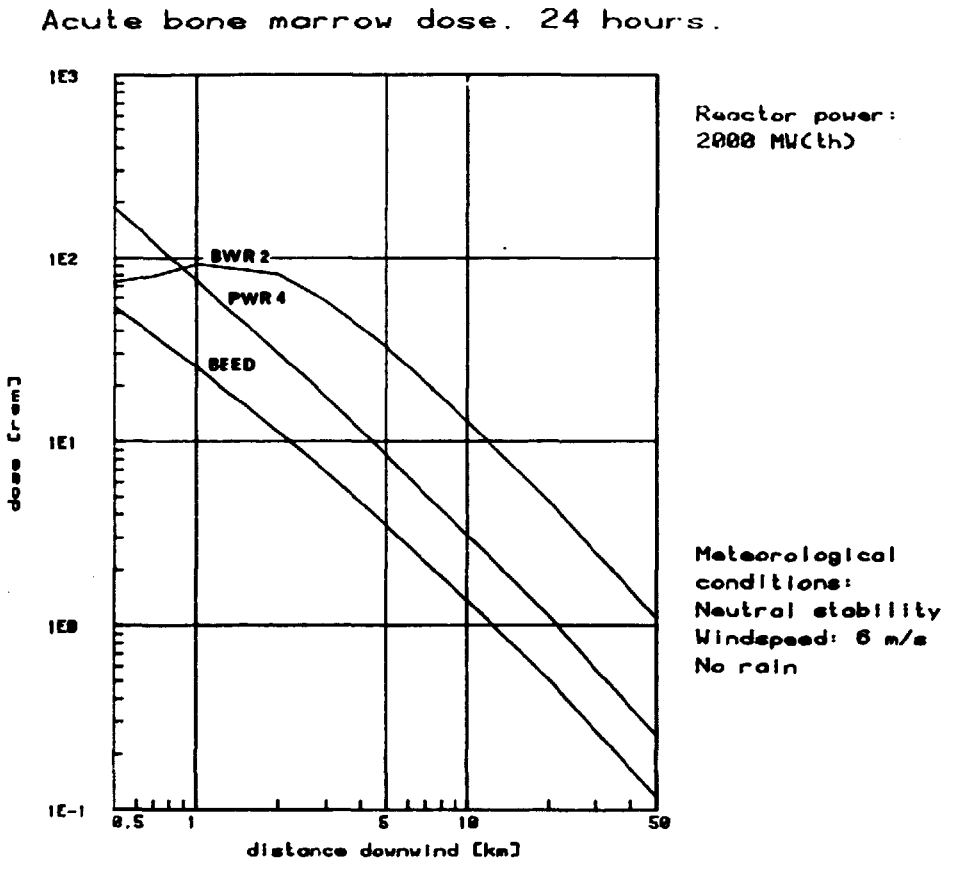

Fig. 4.2

4.2

Total acute bone marrow doses to individuals from the BWR-2, PWR-4, and BEED releases. Inhalation doses are integrated over 30 days. Doses from deposited activity are integrated over the first 24 hours after the release.

Committed effective dose equivalent, 24 hours.

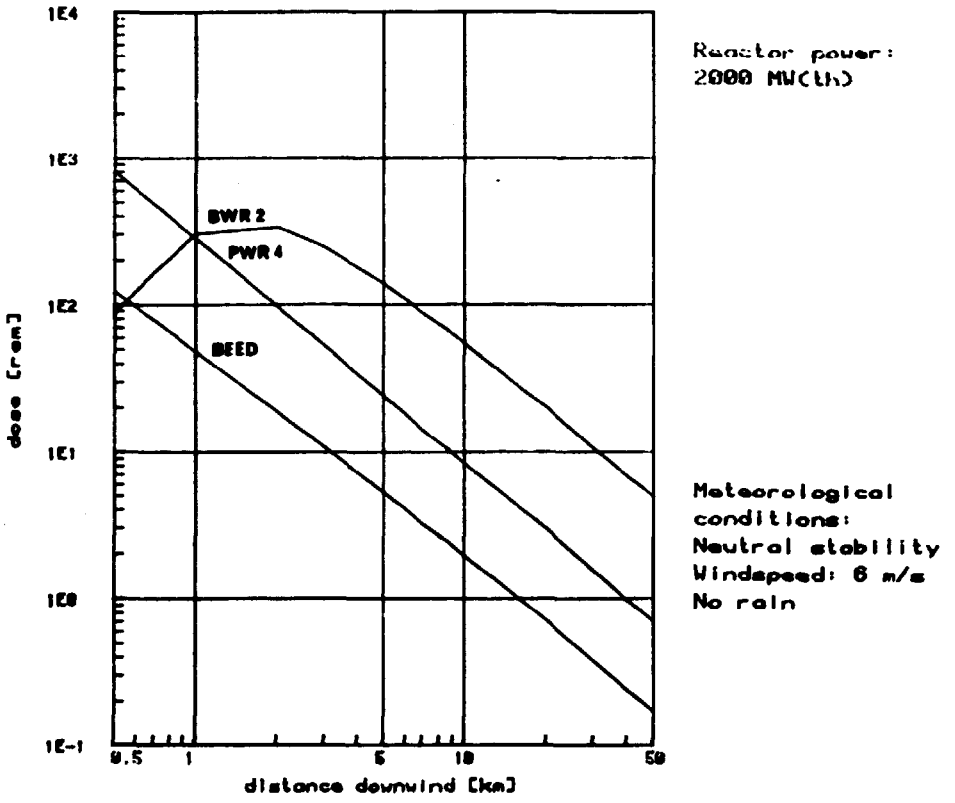

Fig. 4.3

4.3

Total committed effective dose equivalent to individuals from the BWR-2, PWR-4, and BEED releases.

Doses from deposited activity are integrated over the first 24 hours after the release.

Committed effective dose equivalent, 30 days.

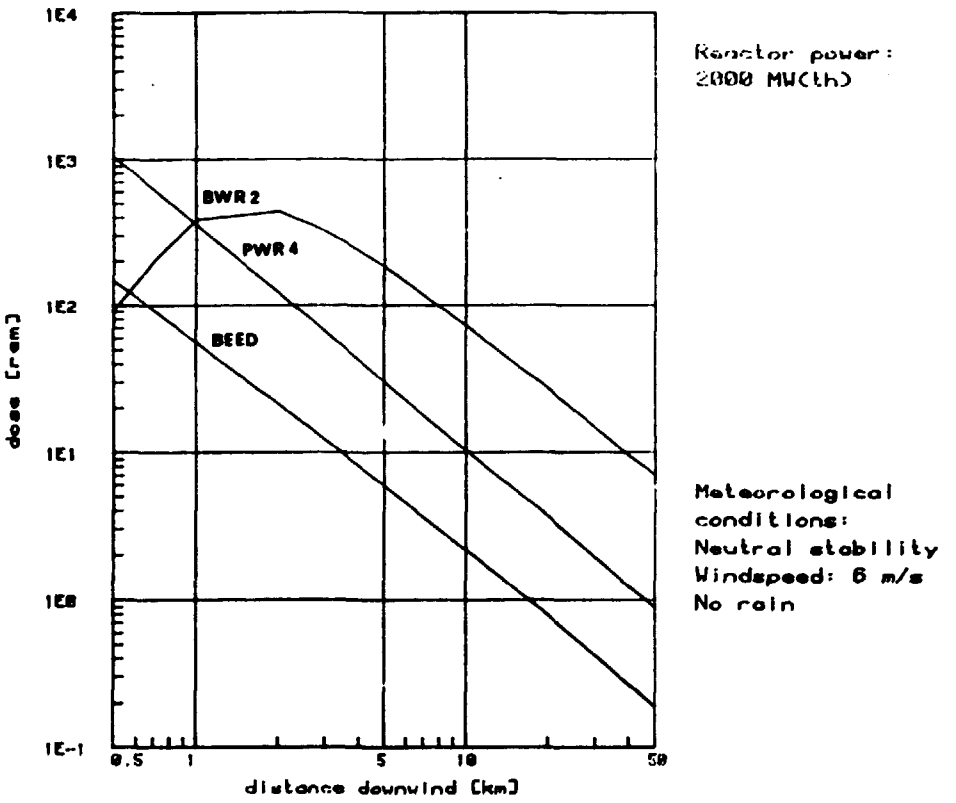

Fig. 4.4

4.4

Total committed effective dose equivalent to individuals from the BWR-2, PWR-4, and BEED releases.

Doses from deposited activity are integrated over the first 30 days after the release.

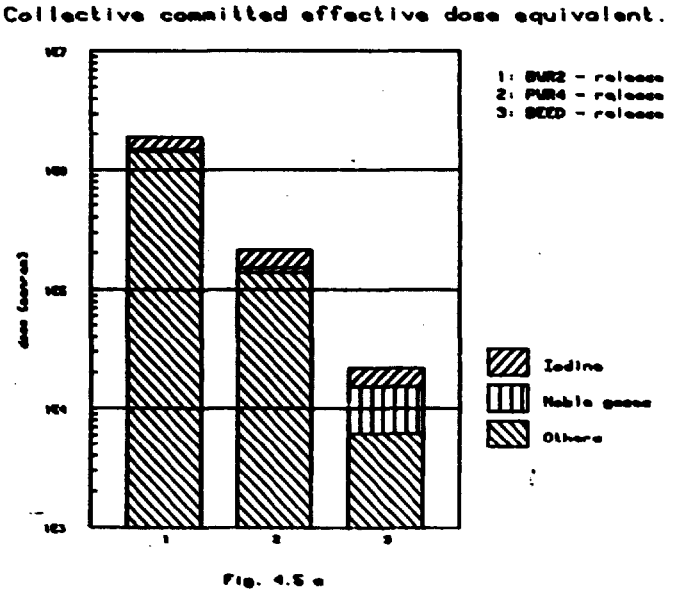

Fig. 4.5 a

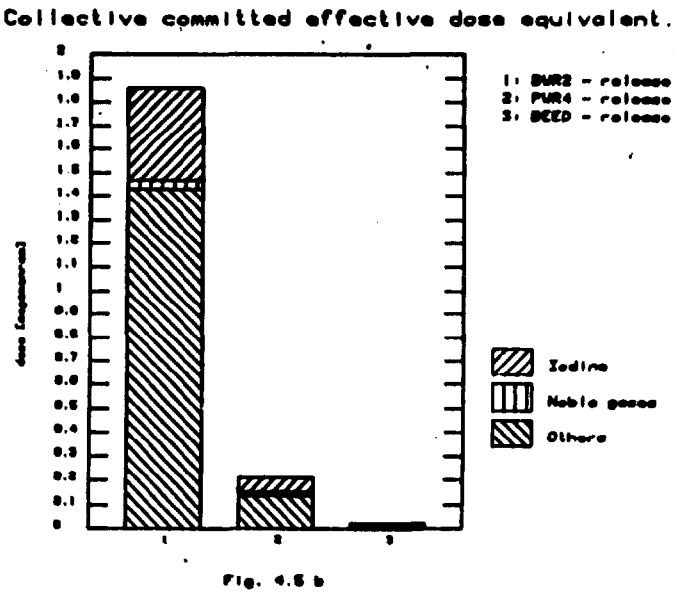

Fig. 4.5 b

4.5

Distribution in isotope groups of collective effective dose equivalent from the BWR-2, PWR-4, and BEED releases integrated from 0.5- to 50-km downwind.
Doses from deposited activity are integrated over 30 years.
Reactor power: 2000 MW(th).
Meteorological conditions: Neutral stability. Windspeed 6 m/s. No rain.

ACUTE BONE MARROW DOSE, 24 HOURS

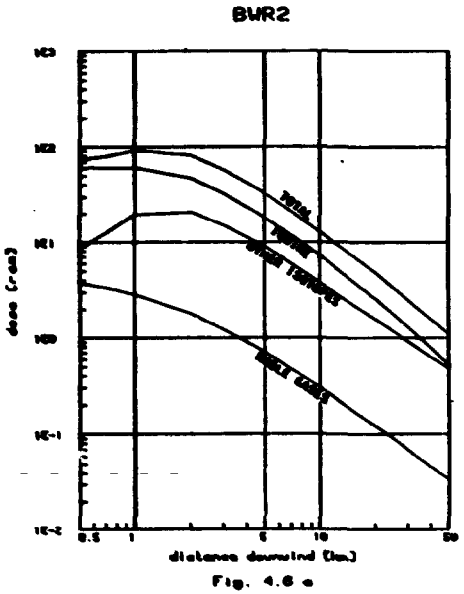

Fig. 4.6 a

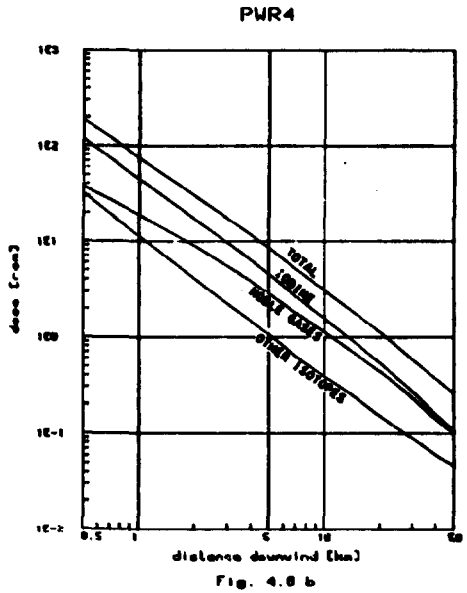

Fig. 4.6 b

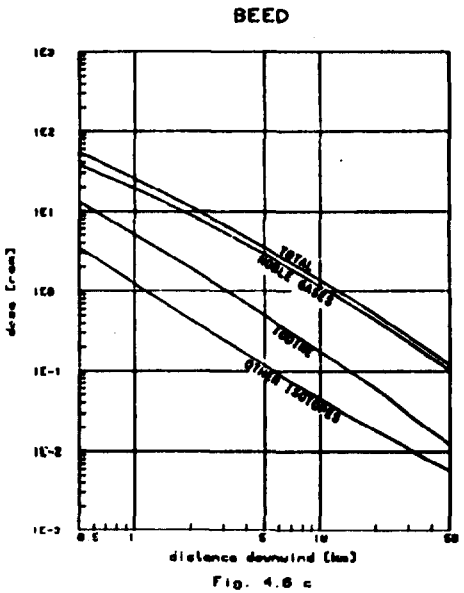

Fig. 4.6 c

4.6

Acute bone marrow doses to individuals distributed in isotope groups for the BWR-2, PWR-4, and BEED releases.

Inhalation doses are integrated over 30 days. Doses from deposited activity are integrated over the first 24 hours after the release.

Reactor power: 2000 MW(th).

Meteorological conditions: Neutral stability. Windspeed 6 m/s. No rain.

24-HOUR DOSES

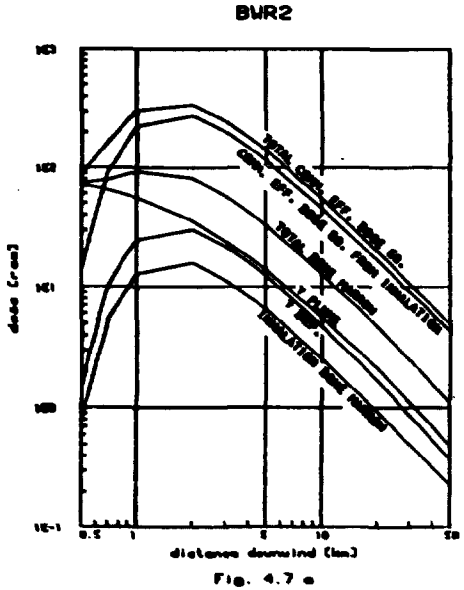

Fig. 4.7 a

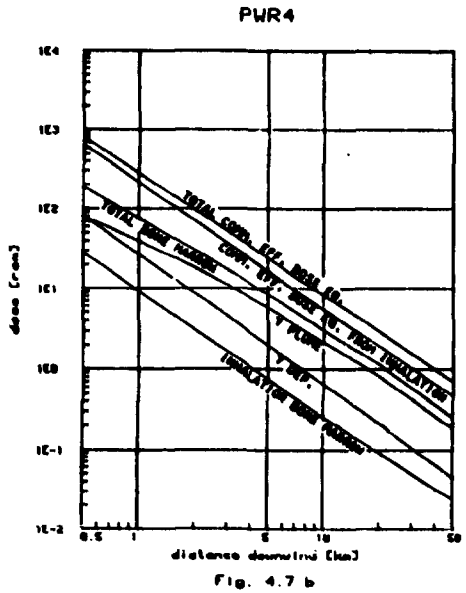

Fig. 4.7 b

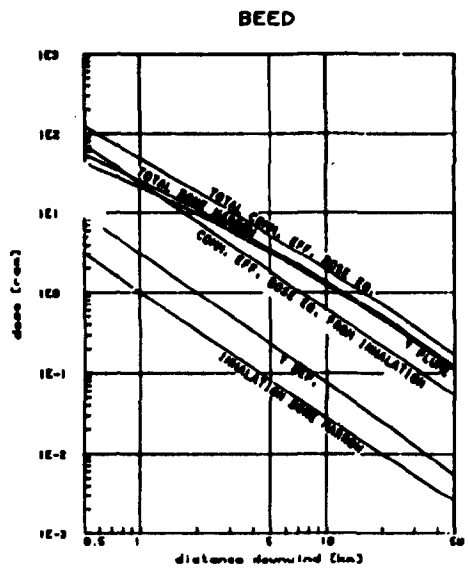

Fig. 4.7 c

4.7

Committed effective dose equivalent and acute bone marrow doses to individuals split in dose components for the BWR-2, PWR-4, and BEED releases.

Inhalation doses to bone marrow are integrated over 30 days. Doses from deposited activity are integrated over the first 24 hours after the release.

Reactor power: 2000 MW(th)

Meteorological conditions: Neutral stability. Wind speed: 6 m/s. No rain.

COMMITTED EFFECTIVE DOSE EQUIVALENT, 30 YEARS

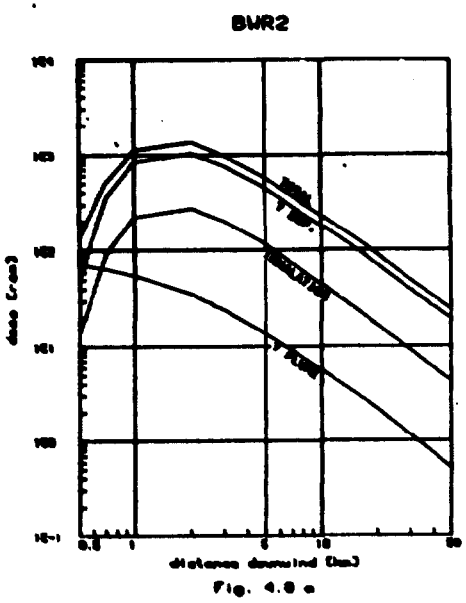

Fig. 4.8 a

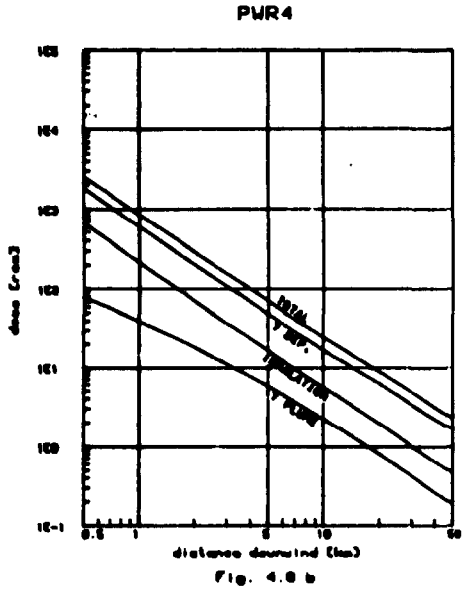

Fig. 4.8 b

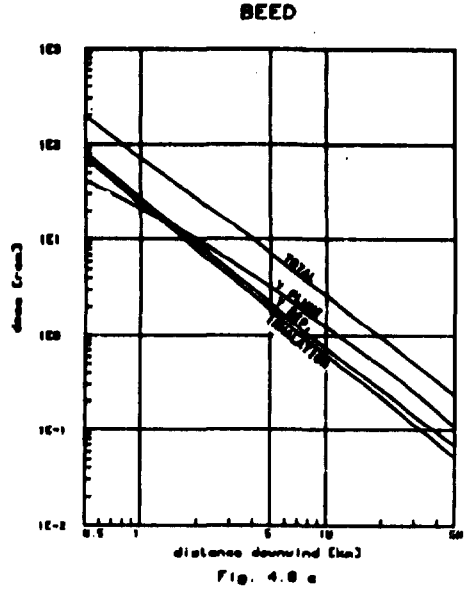

Fig. 4.8 c

4.8

Committed effective dose equivalent to individuals split in dose components for the BWR-2, PWR-4, and BEED releases.

Doses from deposited activity are integrated over 30 years.

Reactor power: 2000 ME(th)

Meteorological conditions: Neutral stability. Wind speed: 6 m/s. No rain.

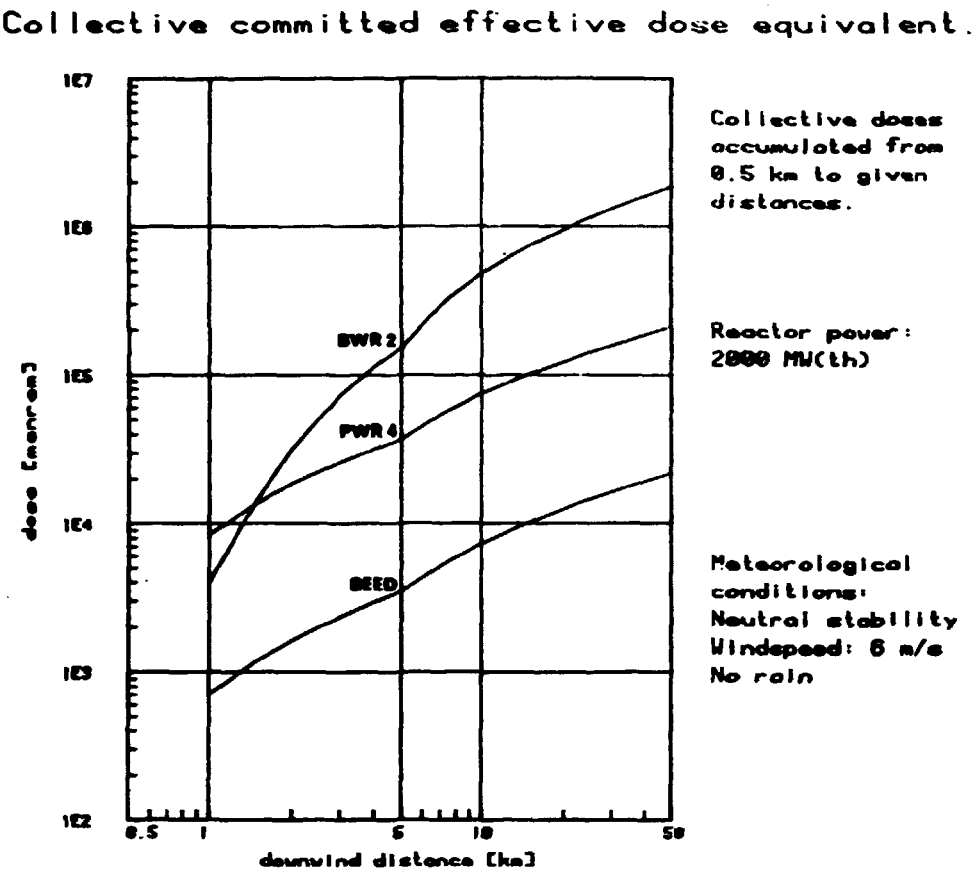

Fig. 4.9

4.9

Accumulated collective committed effective dose equivalent as function of distance for BWR-2, PWR-4, and BEED releases. Doses from deposited activity are integrated over 30 years.

APPENDIX

RELEASES EXPERIENCED IN REACTOR ACCIDENTS

H.L. Gjørup

1. Introduction

The releases of iodine and other radionuclides during postulated severe accidents in commercial light-water reactor nuclear power plants appear to have been overestimated in the WASH-1400 study (NRC, 1975).

A reconsideration of actual releases to the environment in past reactor accidents, in particular those experienced at Three Mile Island, SL-1, and Windscale, indicates that natural fission product removal mechanisms, such as chemical reactions, aerosol settling, and the effects of moisture are effective to a degree unaccounted for in the conservative calculation models used so far.

2. Three Mile Island

After the Three Mile Island accident it was noted (Kemeny et al., 1979) that the release of iodine to the atmosphere was 5-6 orders of magnitude smaller than the release of noble gases, although the inventories of iodine and noble gases were of the same order of magnitude.

In a letter to NRC chairman Ahearne, dated August 14, 1980, three of the scientists that served at the technical staff of the Kemeny Commission offered an explanation (Stratton et al., 1980). They believe that the iodine in the hot fuel rods reac-

ted with cesium (which was in excess in proportion to iodine) to form cesium iodide and that it emerged from the fuel as cesium iodide vapour which would be expected to condense or "plate out" when it reached metal surfaces at temperatures at or below 400-500°C, entering finally into solution as soon as water or condensing steam was encountered. If the iodine was not already present in the fuel as iodide it would be converted to this form when escaping from the fuel and remain as such because of the chemically reducing environment. The vapour pressure of iodine over a solution of (cesium) iodide is very low and this is the explanation of the exceedingly small release of iodine in the Three Mile Island accident. They finally state that this qualitative picture is consistent with the small escape of iodine observed in a number of incidents when water was present, and they believe that an accident involving hot fuel and a water or steam-water environment will have the same controling chemical conditions as did the TMI-2 core and primary system. The iodine will emerge as cesium iodide (and possibly in other iodide forms) and enter into solution as soon as wet steam or water is encountered. It will persist in solution as nonvolatile iodide as long as oxidizing conditions do not prevail.

The Three Mile Island accident also initiated a report from EPRI (Levenson and Rahn, 1980). The authors of this report observe that experience has shown natural phenomena to be very effective in containing radioactivity. These phenomena are chemical reactions, aerosol settling, effects of moisture, etc. The authors state that the same natural barriers, which acted in the Three Mile Island accident will also act in future accidents. As a result present estimates of radiation exposures in connection with core melt-downs may be too high by a factor of ten or more.

A number of cases of radioactivity releases from damaged reactors, experimental reactors tested to destruction and controlled experiments, are mentioned as supporting evidence by Levenson and Rahn (1980) and by Stratton et al. (1980). Most notable among these cases are two major reactor accidents that resulted in radioactive releases to the environment, namely the SL-1 acci-

dent which occurred at Idaho National Reactor Testing Station in January 1961 and The Windscale accident which occurred in October 1957.

Principally as a result of the above-mentioned letter and report, chairman Ahearne directed the staff of the NRC to prepare a report, as a first step towards resolving the issues. This report appeared as a draft in the beginning of March 1981 (NUREG-0772, 1981). Unfortunately, fission product behavior during previous reactor accidents and destructive tests were not analysed in the draft report. It was stated, however, that the current data base supported the conclusion that cesium iodide is expected to be the predominant iodine form under postulated light-water reactor accidents. At the same time, however, it was also concluded that the assumed form of iodine does not have a major influence on the estimated iodine release to the environment for the risk-dominant accidents. The report said that the analyses indicated that the best estimate attenuation factor for iodine is between 2 and 10 for the risk-dominant accidents (i.e., 10% to 50% of the core inventory of iodine could be released to the environment).

3. SL-1

The most pertinent reactor accident not taken into account in the above-mentioned report (NUREG-0772) is the SL-1 accident. A power excursion melted and partly evaporated ca. 19% of the core material. Three per cent of the total core inventory corresponding to ca. 15% of the inventory in the melted material (measured as γ-activity) was later found in a finely dispersed form on the floor and walls of the reactor building (IDO-19311, 1962). The water inventory in the reactor was quite low - about 215 litres in the core and 3,800 litres in the total system (IDO-19302, 1962). Upon inspection following the accident it was found that no water was left in the reactor tank (96th Congress, Serial No. 96-14, 1980); later investigations showed that approximately 2 kg of uranium-235 was missing from the active core region, most of this from 16 fuel elements in the centre.

The original total core inventory was 14 kg of uranium-235 (IDO-19311, 1962). About 3 m^3 of water was released very quickly as part of the steam hammer which raised the entire pressure vessel about 3 m into the reactor room. The peak pressure of the water was estimated at 680 atmospheres (Horan, 1981).

Under these circumstances it is reasonable to assume that 100% of the iodine and cesium in the melted material was released to the reactor building. The initial total core inventory at the time of the accident was 28000 Ci of iodine-131 and 3100 Ci of cesium-137 (Levenson and Rahn, 1980). Under the above-mentioned assumptions, the release to the reactor building was thus about 5300 Ci of iodine-131 and 600 Ci of cesium-137. There was no containment and the reactor building was "drafty" and vented to the atmosphere. The ventilation rate was approximately 640 m^3/h, and since the volume of the room was 425 m^3 this corresponds to 1.5 volume changes per hour. Although about 3 tons of water were injected into the reactor room no one reported any evidence of water on surfaces during the first entries, nor did photos taken within the first few hours give any indications such as, e.g., reflexions. A small amount of steam was seen coming from the building exhaust by the firemen on arrival at the reactor building about eight minutes after the excursion (Horan, 1981).

Nevertheless, only about 20 Ci of iodine-131 and 0.5 Ci of cesium-137 was released to the atmosphere during the first 24 hours after the accident and about 50 Ci iodine-131 more during the next 30 days (Horan and Gammill, 1963). The release percentage of iodine-131 to the atmosphere was thus only 0.4% of the 5300 Ci injected into the reactor room and the release percentage of cesium-137 to the atmosphere only 0.1% of the 600 Ci injected into the reactor room. It seems likely that these small release percentage can be explained as the result of two circumstances alone: (1) that iodine emerged from the fuel as iodide (probably cesium iodide), and (2) that water was present (although in a limited amount) during the release to the reactor room. It is noteworthy that a volatile element like tellurium seems to have been almost entirely absent in the release to the atmosphere (Horan, 1981).

4. Cesium release

In order to explain the low release to the atmosphere of cesium in relation to iodine in the SL-1 accident a new concept is introduced here, namely, the idea that while the total release percentage for iodine was essentially the same as that for cesium iodide then the percentage for all other cesium compounds together was much lower. This meant that the total release percentage for cesium was determined to a high degree by the extent to which it was carried away by iodine as cesium iodide.

In a reactor that has been running for some time about 0.8% of the fission product atoms are iodine atoms, mainly stable and long-lived ones (0.1% ^{127}I and 0.7% ^{129}I); 19.6% are cesium atoms (7% ^{133}Cs, 6.6% ^{135}Cs, and 6% ^{137}Cs), i.e. the ratio is 1/25 as far as the number of iodine and cesium atoms in the fuel are concerned. In cesium iodide the same ratio is 1/1. This means that the ratio of iodine to cesium atoms in cesium iodide <u>formed</u> in the fuel is 25 times larger than that of all the iodine and cesium atoms <u>present</u> in that fuel. This is true for any set of iodine and cesium isotopes, e.g. for iodine-131 and cesium-137 which are the isotopes of principal interest with respect to radioactivity. It follows that the ratio of iodine-131 to cesium-137 radioactivity in any cesium iodide formed in the fuel is 25 times larger than the same ratio in the fuel as such.

In the case of the SL-1 accident the amounts of iodine-131 and cesium-137 radioactivity in the fuel at the time of the accident were, as mentioned above, 5300 and 600 Ci, respectively. Therefore the ratio of iodine-131 to cesium-137 radioactivity in cesium iodide formed in the fuel should be:

$$\frac{5300 \times 25}{600} \approx 220$$

The ratio of iodine-131 to cesium-137 radioactivity found in the material actually released was 40 if you refer to the first 24 hours and 140 if you refer to the first month. Stratton et al. (1980) describe the SL-1 accident as one in which the chemical nature of the environment (water, steam, air) was at first reducing and subsequently oxidizing. If this is true it is conceivable that some of the cesium iodide originally trapped in the reactor building might have oxidized when the reactor building dried out, thereby releasing iodine. This would explain the rising iodine-to-cesium ratio with time in the released material. It is doubtful, however, if this ratio were really lower in the beginning since the reported amount of released cesium was based on the measurements of soil samples covering the entire release period, which would have been approximately 30 days (Horan, 1981). There is no evidence that the cesium release should have been limited to the first 24 hours after the accident. It could just as well have been released together with iodine over the entire release period. The continuing release of iodine (and cesium?) could probably have been prevented, however, by keeping the reactor building moist inside.

In view of the uncertainty with which the released amounts were measured, the calculated ratio of 220, and the measured ratio of 140 (or even 40) are in reasonable agreement with the proposed idea that cesium is released to a large extent as cesium iodide. Other cesium compounds presumably constituted at least 96% of the total cesium inventory. Apparently they were released to the atmosphere to a much lesser extent than cesium iodide.

5. The Windscale accident

The large release of iodine to the atmosphere in the case of the Windscale accident (about 12% of the inventory in the 8 tons of fuel were assumed to be involved) is usually explained as a result of oxidizing conditions in the pile presumably giving rise to large releases of elemental iodine (Stratton et al., 1980; Levenson and Rahn, 1980; NUREG-0772, 1981). This

picture is probably wrong. The graphite and the fuel in the affected region of the pile were very hot, about 1300°C (Atomic Energy Office, 1957), and the air-flow restricted to a minimum. The graphite and fuel were oxidized and the air that did flow through the core was reduced; but since graphite and fuel were in excess, the conditions in the pile should be regarded as chemically reducing with respect to the cesium iodide escaping from the fuel.

Apparently, the cesium iodide released from the fuel was rather stable and was still intact when released to the atmosphere. Clark (1974) reports that the amount of non-gaseous nuclides retained on the filters of the Windscale pile and the amount released to the atmosphere were about the same (i.e. about 50 per cent filtering efficiency). The filters were designed to remove only the larger particles. With respect to the activity of iodine-131 and cesium-137 20000-30000 Ci and 800-1000 Ci, respectively, were retained on the filters, and 20000 Ci and 600 Ci, respectively, released to the atmosphere (Clark, 1974). The ratio of iodine to cesium in the activity retained on the filters is thus, for all practical purposes, the same as that of iodine to cesium in the activity released to the atmosphere. It is unlikely, therefore, that iodine was released to the atmosphere to any appreciable extent either as a gaseous compound or in its elemental form.

It is evident, however, that cesium was released to the atmosphere in amounts larger than can be explained by the release of cesium iodide alone. The radioactivity in the involved part of the fuel (8 tons) was estimated to be 162000 Ci of iodine-131 and 12300 Ci of cesium-137 (Clark, 1974). The activity ratio of iodine-131 to cesium-137 in cesium iodide formed in this fuel would therefore be (162000/12300)x 25 ≈ 330. The activity released was 20000 Ci of iodine-131 and 600 Ci of cesium-137 (Steward and Crooks, 1958). The ratio was thus 33, i.e. the amount of cesium released was 10 times larger than that which could possibly be explained as carried away by iodine as cesium iodide, if all the iodine (100% of that present in the fuel) had reacted with the corresponding amount of cesium (4% of that

present in the fuel). Other cesium compounds must therefore have been involved.

The large difference in cesium iodide release (and the even larger differences in the releases of other cesium compounds and elements like tellurium) between the SL-1 and the Windscale accident can be explained, however, by the lack of water at Windscale (before the fire finally was put out by pouring large amounts of water into the pile thus stopping the subsequent release of iodine!). At SL-1, on the other hand, some water was present, although in small amounts. The steam-water mixture ejected from the reactor vessel at the time of the accident was obviously sufficient to limit drastically the radioactivity released to the atmosphere.

6. Summary and conclusion

In the Three Mile Island accident the release of iodine to the atmosphere was surprisingly low compared with the release of noble gases. This was explained by Stratton et al. (1980) as a result of the iodine being released as cesium iodide from the fuel to a reducing and wet environment in a containment with reasonably maintained integrity.

In the SL-1 accident the immediate release of iodine-131 to the atmosphere was relatively much larger. In addition, a significant amount of cesium-137 was released. A comparison of the ratios of iodine to cesium in the fuel and in the release suggests that the cesium release was determined to a high degree by the extent to which it was carried away by iodine as cesium iodide, whereas other cesium compounds were not released to a comparable extent. Despite the sweeping action of the normal room ventilation and the short sweeping burst generated when water and steam were expelled from the reactor vessel, the release percentages were surprisingly small.

In the Windscale accident the release of iodine was again relatively larger than in the SL-1 accident. A consideration of

the conditions in the pile at the time of the accident and a comparison of the ratios of iodine to cesium on the filters and in the release to the atmosphere suggests that iodine was released in a particulate form presumably as cesium iodide. A comparison of the ratios of iodine to cesium in the release and in the fuel shows that the cesium release was not limited to the release of cesium iodide; in fact, the release of other cesium compounds was at least 10 times larger.

The essential difference between the Windscale and SL-1 accidents is that at Windscale no water was present while at SL-1 a steam-water mixture was expelled from the reactor vessel into the reactor building. The scavenging action of this mixture was apparently sufficient to precipitate about 99% of the cesium iodide and even more of other cesium compounds and compounds of other radioactive elements, such as tellurium. A contributing circumstance might have been that at Windscale the activity was drawn out through the chimney by the natural draft during the short intervals when the fan dampers were opened in an attempt to cool the pile, while at SL-1 the transport of activity to the atmosphere was essentially limited to the action of the reactor room ventilation system.

As mentioned in Section 2.2 of this report it appears that the most serious consequences of a core meltdown would be a result of a failure to isolate the containment. It is difficult to imagine a containment isolation failure more serious than having no containment at all as in the SL-1 case, and it is also difficult to imagine an LWR with relatively less water present than in the SL-1 case. It is concluded, therefore, that it seems credible that the release percentages in a serious meltdown accident in a modern LWR reactor would not be larger than those experienced in the SL-1 accident, i.e., 1% of iodine, 0.1% of cesium, and 0.02% of barium-strontium. It is estimated that the release of lanthanum and ruthenium could be at the same level as barium-strontium, while tellurium probably would lie somewhere between iodine and cesium, say 0.5% of the core inventory.

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CALCULATION OF DOSE CONSEQUENCES OF A HYPOTHETICAL LARGE ACCIDENT AT A NUCLEAR POWER REACTOR

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Department or group

The Departments of Reactor Technology and Health Physics

Group's own registration number(s)

46 pages + tables + illustrations

Abstract

The fission-product release to the atmosphere from a nuclear reactor during a hypothetical large accident is discussed, and the consequences in terms of doses to the population are calculated. The reactor is a light-water reactor located at a site representing an idealized, simplified Danish location.

Three release categories are discussed: The first is the release in an accident with a core meltdown and a major rupture of the containment. This release is represented by the BWR-2 release of WASH-1400. The second is the release where the containment integrity is maintained, but there is a failure to isolate the containment. This release is represented by the PWR-4 release. The third is obtained as a best estimate from empirical data, and it is called the BEED release. The release of the BEED case is deduced from empirical evidence - especially the SL-1 accident - in a separate study which is described in the appendix. The release fractions for the most significant elements such as iodine and cesium decrease by a decade from BWR-2 to PWR-4, and from PWR-4 to BEED, while the release fractions of the noble

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Health Physics 50

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gases are assumed to be at an almost constant high level.

The dose consequence in terms of a long-term committed effective dose equivalent is found to be practically directly proportional to the release fractions, i.e. decreasing by a decade from BWR-2 to PWR-4, and from PWR-4 to BEED. For the acute bone marrow dose the contribution from the noble gases is significant in all three cases, and as the noble gas release is almost constant the decrease from one case to the next is of the order of only half a decade. For the BEED case the noble gases, which give an external gamma dose from the plume, are the most significant radioactive fission products, both for long-term and acute doses. For the BWR-2 and PWR-4 cases the I-131 in the plume is predominant in the acute dose, while Cs-137 deposited on the ground is the main contributor to the long-term dose.